



DE 199 56 654.2
(US 09/889,956)

CERTIFICATION

I, ANTJE KOPP, Technical Translator and Interpreter, having successfully passed the State Examination for Translators and Interpreters of the Federal Land of Bavaria, and duly appointed by, sworn to and commissioned by the President of the Landgericht [*Regional Court*] of Muenchen I,

of Taimerhofstrasse 10, D-81927 Muenchen and having my office at Ismaninger Strasse 27/I, D-81675 Muenchen, Germany,

do hereby declare that I am a professional translator, fully competent to translate from German into English and fully conversant with the German and English languages, and I do herewith certify that the following translation is, to the best of my ability and knowledge, a true and correct English rendition, in every particular, of the priority certificate issued by the German Patent and Trade Mark Office on August 25, 2004 in relation to the German Patent Application DE 199 56 654.2, filed in the name of Fraunhofer-Gesellschaft zur Foerderung der angewandten Forschung eV, 80636 Muenchen (DE) and entitled

Method for producing micro-mechanical and micro-optic components consisting of
glass-type materials

which is equally attached.

Muenchen, this 23rd day of September 2004.

Antje Kopp
Ismaninger Strasse 27/I
D-81675 Muenchen
Federal Republic of Germany



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FRAUNHOFER-GESELLSCHAFT
zur Foerderung der angewandten Forschung e.V.
Leonrodstrasse 54
D-80636 Muenchen

Method for producing micro-mechanical and micro-optic
components consisting of glass-type materials

The present invention relates to a method of producing micro-mechanical and micro-optic components and/or functional elements consisting of glass-type materials, which permits the duplication modelling of structured substrate surfaces in glass, with utilisation of the flow properties of the glass and with application of standard methods in semiconductor technology. The term "functional element" is meant to denote a substrate with a structured surface in accordance with the present invention, which consists of glass-type material and is used in further-going steps of method.

Shaping methods, e.g. in mono-crystalline silicon, are widely common as standard methods in semiconductor technology. For transmissive micro-optical components such as lenses, optical gratings or beam shapers, however, semiconductor materials are suitable only conditionally. Silicon, for instance, presents a strong absorption in the visible range of wavelengths of the light. Optical components for wavelengths

between 380 nm and 760 nm are thus made of materials similar to glass. The numerous expedient material properties of glass - such as a low coefficient of thermal expansion or a high mechanical and chemical stability - are also expediently employed in micro-mechanical components. The production of such components is limited, however, insofar as suitable methods are available only conditionally with respect to the micro-structuring of glass-type materials. In particular, the standard methods known from semiconductor technology are ruled out because suitable etching processes for achieving comparable structure levels are not known for glass-type materials.

Prior Art

For the production of micro-optical as well as micro-mechanical components, mechanical operations such as grinding, sawing, polishing and scribing are applied in accordance with prior art (e.g. echelette grating). As a result, however, both the precision and the variation of shapes are strongly restricted.

Hot relief printing of glass, which is employed for the mass production of macroscopic objects, is not appropriate for the production of micro-optical or micro-mechanical components in the order of less than one millimetre because of the lack of suitable materials for the production of the relief printing matrices and as the detachment of the glass from the relief printing matrices results in poor surface qualities.

One method of producing micro-optical systems is based on the production of three-dimensional structures in resist layers by means of grey-tint lithography and the subsequent transfer of the structure into the glass substrate underneath by application of an RIE plasma process (US Patent 5310623). Another method of producing micro lenses as well as micro-lens arrays makes use of resist arrays caused to fuse and thus forming lens-shaped topographies that are subsequently transferred into the substrate underneath by means of an etching process. In terms of the component height, both methods are restricted to a few tens of micrometers and therefore they

are also limited in terms of their lateral dimension. Apart therefrom, the etching process increases the surface roughness.

Solved problem

The present invention is based on the problem of proposing methods of producing micro-mechanical and micro-optical components and/or functional elements consisting of glass or glass-type materials that permit the precise and low-cost shaping of the elements down to the sub- μm range, whilst the height of the elements may amount to a few hundreds of micrometers, as well as the problem of providing the elements produced by this method.

Description

In accordance with the present invention, this problem is solved by the features defined in Claim 1. Components and/or functional elements produced by this method are defined in the Claims 11 to 16.

The preferred embodiments are the subject matters of the dependent Claims.

The inventive method operates on standard lithographic and etching processes for the production of negative moulds (master structures) from a substrate, preferably a semiconductor substrate, e.g. of silicon. In the following, the term "semiconductor substrate" will be used, however with out any restriction of the general applicability. Due to the combination of standard bonding techniques, preferably anodic bonding with a flow process at an elevated temperature, the master structures are transferred into glass or glass-like materials. The negative moulds present a surface structure laterally reversed to the desired surface structure of the glass material, which means that at locations where recesses are present on the surface of the semiconductor substrate projections are created in the glass material on the surface facing the semiconductor substrate. The negative moulds are preferably produced from monocrystalline silicon. To this end, a large number of possibilities is available for proc-

essing of almost any surface structure whatsoever, due to the combination of lithographic processes with wet chemical isotropic as well as anisotropic etching methods and various dry etching processes.

In a similar manner, it is possible to create optical lenses with an extremely low surface roughness and in a size smaller than one millimetre. At lower temperatures or shorter annealing intervals, the glass-type material slowly lowers into the cavities on the substrate, forming defined lens-shaped surfaces. The cavities may be interconnected by channel systems so as to ensure the same process pressure at any location. The lowering depth, which determines the focal length of a lens so produced, may be precisely adjusted by setting the temperature, the pressure and the annealing interval. A subsequent polishing step equalises the dents forming on the face turned away from the substrate so that after removal of the substrate by etching micro lenses and micro-lens arrays are present on the glass in any variation in shape whatsoever. Generally, borosilicate glass, such as Pyrex[®] glass, is used for the process as this type of glass displays a small thermal expansion characteristic in correspondence with the thermal expansion of silicon. The bond established between the glass and the semiconductor substrate then remains particularly stable during the annealing operation. By the term "glass-type" material, however, any material is to be understood that presents the expedient material properties of glass at least in parts, and that presents viscous flow properties under the influence of an increase in temperature and/or under the action of a pressure difference, e.g. glass-ceramics.

The inventive method consists of the follow process flow:

- Conventional lithographic processes are employed to transfer digital or continuous structures into a photo sensitive resist that is applied on a semiconductor substrate, preferably a mono-crystalline silicon wafer. Standard methods are available for transferring digital structures, which are the common contact or projection exposure processes usually employed in the semiconductor industry.

When grey-tint lithography is applied it is possible to structure surfaces of almost

any shape whatsoever. After exposure, the resist volume that was not exposed is removed in a developer bath.

- With the application of etching processes, the topography of the resist layer is transferred to the semiconductor substrate. This may be done by both wet chemical etching processes (e.g. etching in baths containing hydrogen-fluorine compounds) and dry etching methods (plasma etching, reactive ion etching).
- The structured semiconductor substrate is bonded to a substrate consisting of a glass-type material (glass substrate), e.g. a Pyrex[®] wafer, preferably by means of the anodic bonding technique, so that a hermetically tight bond will be created between the semiconductor substrate and the glass substrate. This is done under conditions resembling those of a vacuum or by negative pressure. After bonding, the pressure prevailing throughout the bonding operation in the process chamber is preserved in the recesses of the surface structure of the semiconductor substrate. With the anodic bonding technique, two extremely planar substrates are heated on a so-called hot plate, which is a conductive substrate (e.g. a semiconductor substrate) and a non-conductive substrate (e.g. a glass substrate). Additionally, a voltage of up to 1,000 Volt is applied between the substrates. When the negative pole is present on the glass substrate the positive mobile ions (e.g. boron, sulphur) present in the glass matrix migrate in a direction towards the cathode. The immobile stationary oxygen ions form a negative volume charge zone on the boundary to the semiconductor substrate. The resulting electrostatic force results in an intimate contact between the two adjacent substrate surfaces. In combination with the effects of an elevated temperature, this results in the formation of chemical bonds between the atoms of the conductor and non-conductor substrates. When additionally an outside pressing force is exerted on the substrates this results in an intensification of the bond.
- By subsequent annealing, preferably at normal pressure, the glass material is heated to a level higher than the vitrifying temperature thereof. Due to its then plastic properties, the glass material fills the apertures in the structured surface of the semiconductor substrate. The annealing interval and the annealing tempera-

ture must be so high that with the given relative pressure conditions between the pressure of the atmosphere in the annealing furnace and the pressure preserved in the recesses of the semiconductor substrate surface during the bonding process, the glass material will flow into the recesses until a relief model of the semiconductor surface structure will be achieved. The propulsive force against the viscous resistance of the plastic glass material mass is the negative pressure prevailing in the apertures, relative to the atmosphere in the annealing furnace. With an identical temperature and process time, the material characteristics of the glass substrate will take the predominant influence on the relief formation and precision of the moulding operation. Particularly the precise composition of the glass, such as the quantity and type of the doping agent (e.g. boron, phosphorous) take an influence on the viscous properties of the glass. Moreover, the moulding characteristics are dependent on the quality of the vacuum during the anodic bonding process.

- The flow of material may give rise to roughness on the glass substrate surface turned away from the semiconductor substrate. If this roughness is not desired it may be removed by grinding and/or polishing processes. For a separation of the processed glass substrate from the semiconductor substrate, a standard etching process may be employed, wherein the silicon is completely removed by etching whilst the glass matrix is retained. To this end various chemicals such as tetramethyl ammonium hydroxide (TMAH) or xenon difluoride (XeF_2) are appropriate.

In a variant of the process, it is possible to produce refractive lenses and lens arrays by partial inflow into a silicon structure. To this end, recesses are etched in the semiconductor wafer by a wet or dry chemical etching process, which are so dimensioned that after annealing the lens-forming bulges in the glass substrate will not contact the walls of the recesses. In the operation of annealing, preferably at normal pressure, the glass substrate bonded to the semiconductor substrate under vacuum or negative pressure, respectively, the glass substrate is heated to 600 to 800 degrees Celsius. In distinction from the aforescribed process, the sinking of the glass substrate into the prepared recesses of the semiconductor substrate is stopped by cooling

when the desired degree of inflow, i.e. the desired lens shape, for example, is reached. Then, after cooling, the glass substrate side turned away from the semiconductor substrate may be planished and the lenses may be exposed by removal of the semiconductor substrate by etching.

Another modification of the process is of interest particularly for structuring micro-mechanical components. This variant of the inventive method may be applied, for example, in the production of curved surfaces for the implementation of effective electrostatic actuators for low-voltage operation, such as those required for the design of micro-relays or micro valves. To this end, the effect may be expediently utilised that very smooth and curved surface shapes are always formed when the glass material flows into the recesses of the semiconductor substrate on that glass substrate surface that is turned away from the semiconductor substrate.

In a varied embodiment of the described method, the glass substrate surface turned away from the semiconductor substrate is not planished after cooling but it is rather used for the further production of the micro-mechanical components. The glass substrate surface, which was bonded to the semiconductor substrate, can be planished after removal of the semiconductor substrate by etching. The further manufacturing steps of the micro-mechanical component(s) are then carried out on the glass substrate surface turned away from the semiconductor substrate. In the case of an electrostatic actuator, initially the driving electrodes are produced in the curved pitches of the glass material. Subsequently, a thin layer is extended and structured over the pitches with these electrodes. This may be done, for example, by anodic bonding of a silicon wafer (e.g. SOI (silicon-on-isolator) wafer) on the glass surface, whereupon the wafer is ground and/or etched down to a thin layer.

The shapes and/or moulds produced in glass or glass-type materials in the aforedescribed manner may, in their turn, serve as functional elements and constitute a master structure for the production of printing and/or injection moulding moulds, e.g. nickel moulds for the injection moulding process. To this end it is preferred that the glass mould, which is produced by partial inflow of the glass material into the surface

structure of the semiconductor substrate, is moulded in a metal, preferably a nickel alloy, in an electroplating process. The metal is here deposited from a solution on the surface to be relief-moulded. After detachment of the glass mould and/or its removal by etching, the metal relief mould so produced constitutes the master mould for products presenting a surface structure and consisting of materials appropriate for such a use, e.g. a synthetic resin, which are to be manufactured in a printing and/or injection moulding operation.

Relief moulding of structured substrate surfaces, e.g. silicon wafer surfaces, in glass is an important and promising method of manufacturing micro-optical components, for example. Utilising the surface topography of a master structure, preferably consisting of silicon, which is produced with inclusion of the advantages of semiconductor technology, structures as small as down to the μm range are transferred to glass-type materials with a high precision. The expedient optical, mechanical and chemical properties such as those of glass can thus be made accessible to the high-precision moulding processes and the manifold potential structuring methods and processes common in semiconductor technology. Another advantage derives from the aspect that after moulding of the glass, the negative mould is removed by an etching process that does not involve a mechanical load on the glass material. This permits the realisation of very deep structures in the glass, which can never be achieved with printing on account of the mechanical load involved.

The method encompasses a combination of method steps that are applied in a particularly low-cost, efficient operation with a high degree of purity and precision by parallel production (batch process) due to mass application in the semiconductor technology. As a result, these advantages are transferred to the inventive method.

The present invention will be described in the following in details by embodiments, without restriction of the inventive idea, with reference to the drawings wherein:

Fig. 1 illustrates a schematic process flow for relief moulding of a structured surface processed in a semiconductor substrate on a glass-type material,

- Fig. 2 shows a schematic process variant wherein a lens system, for example, is produced by partial inflow of the glass material into recesses prepared on a semiconductor substrate,
- Fig. 3 represents a process variant for the production of a micro-mechanical device,
- Fig. 4 shows an example of a micro-mechanical electrostatic actuator produced in accordance with the inventive method,

Fig. 1 illustrates various stages of a process for the manufacture of a micro-structured glass surface with application of the inventive method for projecting a structured silicon surface. These are manufacturing stages following the completion of the following operating steps:

- (a) formation of a structure in the photo resist (1),
- (b) transfer of the structure by etching the photo resist and the surface of the silicon wafer (2),
- (c) anodic bonding of a Pyrex[®] glass wafer (3) onto the silicon surface structures with recesses (4), preferably under conditions resembling a vacuum,
- (d) annealing and inflow of the glass into the silicon surface structures under the action of overpressure and/or induced by the difference in pressure between the furnace atmosphere and the pressure situation created in the anodic bonding process and preserved in the silicon surface recesses,
- (e) grinding and polishing the glass surface turned away from the silicon, after cooling and subsequent removal of the silicon by etching, e.g. in tetra methyl ammonium hydroxide.

Fig. 2 illustrates different stages in the manufacture of a micro-structured glass surface with application of a variant of the inventive method for the production of a micro-lens array in glass. These are manufacturing stages joining the completion of the following steps of process:

- (a) structuring the surface of the silicon wafer (2) with recesses,
- (b) anodic bonding of a Pyrex[®] glass wafer (3) on the silicon surface structures with recesses (4), preferably under conditions resembling those of vacuum,
- (c) annealing and partial inflow of the glass into the silicon surface structures without contacting the bottom of the recesses in the silicon material,
- (d) removal of the silicon wafer, preferably by etching, and
- (e) grinding and/or polishing the glass wafer surface turned away from the silicon material.

The process steps (d) and (e) may also be applied in a reverse order.

Fig. 3 illustrates various stages in the production of a micro-structured glass surface with application of a further variant of the inventive method, which is preferably employed for the manufacture of micro-mechanical components. These are manufacturing stages joining the completion of the following steps of method:

- (a) structuring the surface of the silicon wafer (2) with recesses,
- (b) anodic bonding of an appropriate glass such as a Pyrex[®] glass wafer (3) on the silicon surface structures with recesses (4), preferably under conditions resembling those of vacuum,
- (c) annealing and partial inflow of the glass into the silicon surface structures without contacting the bottom of the recesses in the silicon material,
- (d) removal of the silicon wafer, preferably by etching, and
- (e) grinding and/or polishing the glass wafer surface that had been bonded to the silicon wafer.

The process steps (d) and (e) may also be applied in a reverse order or omitted entirely.

Fig. 4 is a cross-sectional view of a micro-mechanical electrostatic actuator, e.g. of the type used as micro-valve or micro-relay, which is manufactured in correspondence with the inventive method. To this end, the flow of process steps is carried out, which is illustrated in Fig. 3. The electrostatic actuator consists of a glass substrate

(3) with a recess (4) produced according to the invention. Curved metal electrodes (6) are preferably deposited as a layer in the recesses by means of a standard process in semiconductor technology. Then, an electrically conductive resilient membrane (actuator) is stretched over the recesses containing the electrodes. This may be done by anodic bonding of a silicon wafer or an SOI (silicon-on-insulator) wafer on the glass substrate and by subsequent thinning of the wafer to a thickness of a few micrometers. The membrane then consists of a silicon layer (8) isolated from the electrodes by means of an insulating layer (7). When a voltage is applied between the silicon layer and the electrodes the membrane is attracted towards the electrode while the micro-valve/micro-relay is commuted.

Completed with 4 sheets of drawings

List of reference numerals

- 1 photo resist
- 2 silicon wafer, generally the first substrate
- 3 glass substrate
- 4 surface structure of the first substrate, with recesses
- 5 recess
- 6 curved metal electrodes
- 7 insulating layer
- 8 silicon layer

Patent Claims

1. Method of structuring surfaces of glass-type materials, comprising the following steps of operation:
 - providing a first substrate (2),
 - structuring at least one surface of said first substrate for forming recesses (4) on the surface,
 - providing a second substrate of glass-type material (3),
 - joining said first substrate to said second substrate of glass-type material, with a structured surface of said first substrate being joined to a surface of said glass-type second substrate in an at least partly overlapping relationship,
 - annealing the substrates so bonded in such a way that said glass-type material will flow into the recesses of said structured surface of said first substrate.
2. Method according to Claim 1, **characterised in** that said first substrate is a semi-conductor substrate and/or that said glass-type material is a borosilicate glass.
3. Method according to Claim 2, **characterised in** that said semi-conductor substrate is a silicon substrate and/or that said borosilicate glass is Pyrex® glass.
4. Method according to at least one of the Claims 1 to 3, **characterised in** that the joining of said first substrate to said second substrate of glass-type material is carried out by anodic bonding and/or that a negative pressure prevailing during the joining process is preserved after joining in the recesses in the surface of said first substrate between said first substrate and said second substrate of glass-type material.

5. Method according to at least one of the Claims 1 to 4, **characterised in that** during the annealing operation overpressure acts upon the surface of said second substrate of glass-type material, which is turned away from said first substrate.
6. Method according to at least one of the Claims 1 to 5, **characterised in that** after the annealing step, said first substrate is removed by etching from said second substrate of glass-type material.
7. Method according to at least one of the Claims 1 to 6, **characterised in that** said annealing process is carried out by controlling the temperature and the duration in such a way that the inflow of said glass-type material into the recesses of said first substrate will be stopped at a desired depth of inflow, without the glass-type material that has flown in contacting the bottom of said recesses.
8. Method according to at least one of the Claims 1 to 7, **characterised in that** the pressure during and/or the temperature and/or the duration of said annealing process are so selected that relief-moulding of said structured surface of said first substrate is carried out on the surface of said second substrate of glass-type material.
9. Method according to at least one of the Claims 1 to 8, **characterised in that** after annealing and/or removal by etching of said first substrate, one surface of said glass substrate is planished by grinding and/or polishing.
10. Method according to at least one of the Claims 1 to 9, **characterised in that** the step of creating a negative mould of at least one of the structured surfaces of said glass-type substrate or parts thereof in metal by means of an electroplating process and the step of removal of said glass-type substrate from the negative metal mould are carried out subsequently.
11. Printing and/or injection moulding mould made of metal, **characterised in that** it is produced by the method according to Claim 10.
12. Printing and/or injection moulding mould according to Claim 11, **characterised in that** the metal is a nickel alloy.

13. Optical and/or mechanical component comprising a surface-structured glass-type substrate or parts of such a substrate, which is produced according to at least one of the Claims 1 to 9.
14. Lens or lens array according to Claim 13, **characterised in** that after the inflow of said glass-type material into the recesses of said first substrate has been stopped at a desired depth of inflow, without the glass-type material flown in contacting the bottom of said recesses, the surface of said second substrate of glass-type material, which is turned away from said first substrate, is planished by grinding and/or polishing.
15. Micro-mechanical component according to Claim 13, **characterised in** that recesses created on the side turned away from said first substrate during the annealing operation are present in the second substrate of glass-type material.
16. Micro-mechanical valve or relay according to Claim 15, **characterised in** that electrodes are disposed in the recesses created on the side turned away from said first substrate during the annealing operation, in said second substrate of glass-type material, and that an electrically conductive resilient membrane is stretched over said recesses.

Abstract of the Disclosure

What is proposed here is a method of structuring surfaces of glass-type materials and variants of this method, comprising the following steps of operation: providing a semiconductor substrate (2), structuring, with the formation of recesses, of at least one surface of the semiconductor substrate, providing a substrate of glass-type material (3), joining the semiconductor substrate to the substrate of glass-type material, with a structured surface of the semiconductor substrate being joined to a surface of the glass-type substrate in an at least partly overlapping relationship, and heating the substrates so bonded by annealing in such a way that an inflow of the glass-type material into the recesses of the structured surface of the semiconductor substrate will take place. The variants of the method are particularly well suitable for the manufacture of micro-optical lenses and micro-mechanical components such as micro-relays or micro-valves.